High-Frequency Sound Interaction In Ocean Sediments

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Award Number: N00014-98-1-0040
http://www.apl.washington.edu/apl.html

LONG-TERM GOAL

Our long-term goal is to develop accurate models for high-frequency penetration into, propagation within, and scattering from shallow water ocean sediments. Reaching this goal requires a better understanding of several fundamental issues important to high-frequency sediment acoustics. These issues include an understanding of the dominant scatterers versus frequency near the sediment surface, the appropriateness of stochastic descriptions of sediment inhomogeneities, the importance of single versus multiple scattering in sediments, the need for poroelastic sediment models, and an understanding of the physical and biological processes that determine sediment structure.

OBJECTIVES

We have five specific objectives. First, identify the dominant subcritical penetration mechanisms in sandy sediments and demonstrate that the penetrating field can be quantitatively modeled based on measured sediment properties (10-50 kHz). Second, identify the dominant backscattering mechanisms (10-300 kHz) and demonstrate that the backscattered field can be quantitatively modeled based on measured sediment properties (10-50 kHz). Third, measure sediment attenuation (80-300 kHz) and determine constraints imposed on sediment acoustic models, such as poroelastic (Biot) models. Fourth, obtain measures of acoustic spatial and temporal coherence within the sediment and demonstrate that these quantities can be quantitatively modeled based on measured sediment properties (10-50 kHz). Fifth, measure backscattering levels from buried spheres in order to test buried-object-detection (10-50 kHz) modeling accuracy.

APPROACH

The objectives are being addressed as part of the ONR High-Frequency Sediment Acoustics Departmental Research Initiative (DRI). Two ocean experiments will be undertaken. The first experiment is designated SAX99 (Sediment Acoustics eXperiment) and is planned for Oct.-Nov. 1999. Field experiments are preferred over laboratory experiments, since the latter would not have realistic sediment properties such as surface roughness and volume inhomogeneities. Environmental conditions

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **High-Frequency Sound Interaction in Ocean Sediments**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,Seattle,WA,98105**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

such as bioturbation, wave/current conditions, and tidal conditions are also not easily duplicated in the laboratory. SAX99 is planned for a site near Panama City, FL. The specific site will be chosen to give a relatively high critical angle, and with a single sediment type (i.e., no significant layering) down to the maximum acoustics penetration depths of interest (of order 1 m). The water depth will be in the range of 15-20 m, which will allow diver installation of instrumentation within the sediment. Measurements will be made of bottom-scattered acoustic fields in the range of 10-300 kHz and of bottom-penetrating fields in the range of 10-50 kHz over several weeks with multiple geometries.

Extensive environmental measurements will be made by a group of investigators to characterize the seafloor down to centimeter scales (and to smaller scales in many cases). This detailed information on sediment properties and structure will be essential for quantitative data-model comparisons. As part of our effort, two pieces of equipment are being developed at APL by DJ Tang for in situ measurements of sediment inhomogeneities: the Acoustic Tomographic Imaging System and the Sediment Conductivity Probe. The former measures the sound speed spatial variation in the sediment volume, and the latter measures the porosity (and thus the density) spatial variation in the sediment. The resolution for both instruments will be about 1 cm. The sound speed spatial variation will be the limiting measurement in terms of resolution for all environmental measurements being considered. This resolution limitation leads to the 50 kHz upper limit for quantitative data-model comparisons given above as part of the objectives.

SAX99 will be a collaborative effort involving many investigators. Nick Chotiros (ARL-UT) will make acoustic penetration and scattering measurements complimentary to ours. Bob Stoll (Columbia Univ.) plans low frequency acoustic measurements to check velocity dispersion predictions of Biot theory. Mike Richardson, Kevin Briggs, and others at NRL-SSC will make environmental measurements too numerous to itemize here, but in particular they will measure the water-sediment interface roughness with stereophotography and the sediment properties needed to define Biot model parameters. Pete Jumars (UW) and Van Holliday (Tracor) will investigate the impact of biological processes within the sediment. Steve Schock (FAU) will use a chirp sonar to study sediment layering in the vicinity of the measurement site. Jules Jaffe (Scripps) will use a laser profiler to examine rapid temporal changes in roughness. Rob Wheatcroft (OSU) will use a time-lapse stereo camera to measure temporal evolution of interface roughness on time scales of hours to days, and digital X-radiography to measure volume inhomogeneities. Tim Orsi (PSI) will study small scale density structures in the sediment using CT scans, and Dick Bennett (SEAPROBE, Inc.) will analyze the sediment microfabric.

In addition to SAX99 in Oct.-Nov. 1999, a site survey will be conducted in July 1999 as part of the final site selection. At the site survey, in addition to many of the measurements above, Paul Johnson (UW) will do wide area discrete profiling for sediment sound speed, density and permeability. Also, Chris Martens (UNC) will examine the sediment concentrations and benthic fluxes for methane and oxygen in an attempt to bound the sediment bubble concentration.

An important aspect of our approach in preparing for SAX99 has been to develop acoustic simulations that account for scattering from water-sediment interface roughness and sediment volume inhomogeneities. Simulations were then used in designing the buried array configurations for acoustic penetration measurements and for measurements of propagation within the sediment.

WORK COMPLETED

Acoustic simulations

Monte Carlo simulations were developed during FY98 that are 3-dimensional and account for scattering from the rough water-sediment interface (Jackson) or from sediment volume inhomogeneities (Tang). Both of these simulation models are based on first-order perturbation theory, but in each case integral equation results show that perturbation theory is valid for the conditions of interest. This was shown previously for the rough surface case (Thorsos) and during FY98 for the volume case by Chris Jones, a graduate student of Darrell Jackson. Simulations have been used to complete an examination of acoustic penetration results reported by Chotiros [1] and to support experimental planning and design for SAX99.

Acoustic measurement systems

To use coherent processing on experimental data obtained with a buried array, the buried hydrophone locations must be known to a fraction of a wavelength, a requirement that has precluded the use of this method in previous high-frequency experiments. A strategy has been developed and tested for determining these locations to the required precision. The strategy has two components: (1) Initial insertion to a position known to within 1 cm, and (2) use of acoustic surveying to determine the positions to even higher precision.

The insertion strategy is to construct a cofferdam through which the sensors are embedded horizontally while not disturbing the top 10 cm of the sediment. This approach was tested in a laboratory tank experiment using a glass bead sediment. Insertion by rod through a guide mounted in the cofferdam with the subsequent retraction of the rod allowed placement of hydrophones to within a 1 cm error radius. A beach test of the cofferdam arrangement was made in early August, 1998. This was followed in late August by a field test at the proposed SAX99 site near Panama City. The tests indicate that hydrophone insertion into the sediment can be readily done to the desired precision.

The viability of the second component has been examined with single realization rough surface simulations to find the resolution to which in-water sources could be used to determine the location of an in-sediment receiver. Single-realization time signals of 20 kHz transmissions were used in a tracking code, and in-sediment receiver locations were determined to within about 1 mm in each of the three orthogonal directions when no source uncertainty was assumed. This indicates that receiver location uncertainty will be dominated by source location uncertainty, since the latter will be considerably greater than 1 mm. The combination of the ability to implant the sensors with precision and then confirm/locate the positions acoustically indicates that coherent processing should be feasible, particularly at lower frequencies (10-30 kHz; wavelengths of 15 to 5 cm).

Environmental measurement systems

Acoustic Tomographic Imaging System: A DURIP proposal was submitted last year to support purchase of an acoustic tomographic system with the required resolution of 1 cm x 1 cm. The proposal was approved and the new system is expected to be delivered by May, 1999. Work has begun on simulations and inversion algorithms for the new imaging system.

Sediment Conductivity Probe: An in situ conductivity probe is being developed under the ONR-ARL program during FY98-99 for use in SAX99. It should be completed by 15 December 1998 and will be used to measure 3-dimensional sediment density spectra autonomously. Motivated by acoustic modeling results, an effort has also been initiated to measure cross spectra between the spatial fluctuations of sediment sound speed and density.

Measurement of sand grain bulk modulus: A new approach for laboratory measurement of sand grain bulk modulus is being developed in joint work with NRL-SSC. The new approach is based on measuring the sound speed in a mixture of sand grains and density-matched heavy liquid. Preliminary results have been obtained.

RESULTS

Acoustic simulations

Simulations using incoherent processing were made of experimental measurements on subcritical penetration reported by Chotiros [1]. He found a penetrating wave with an apparent propagation speed in the sediment of 1200-1300 m/s based on an incoherent processing method. In previous work, we have shown [2] that rough interface scattering can mimic this result with a suitably chosen roughness spectrum. In this work the interface scattering was treated with formally averaged scattering theory, and a roughness spectrum rich in high wavenumbers was required to obtain these slow apparent speeds. With a more typical spectrum an apparent speed of about 1500 m/s was obtained. Now with Monte Carlo simulations the scattering from individual interface realizations can be simulated. The results vary considerably from realization to realization, and even using the more typical roughness spectrum an apparent speed of 1300 m/s is sometimes observed. A paper on this work was submitted to JASA.

Simulations have been used to analyze designs for buried arrays to be used for measurements of acoustic penetration into sediments and of propagation within sediments. For acoustic penetration measurements, one goal is to determine if a coherent component of the penetrating field exists within an incoherent background when the incident field is subcritical. To investigate this issue, simulations have been done that account for scattering by interface roughness, and varying amounts of the acoustic field were put in the form of a slow coherent wave. Sparse arrays, as used in previous measurements [1], were found to produce serious artifacts in speed-angle ambiguity plots whether coherent or incoherent processing was used, and thus are not suitable. Dense arrays, with sub-wavelength spacing, were found to perform well but are thought to be impractical to implement. Synthetic dense arrays obtained by moving the source in small increments [3] were found to produce serious artifacts when incoherent fields were present. Extensive simulation studies led to the following design concept: Hydrophone density in the 3-D array is intermediate with about 30 elements in an array aperture of order 0.5 m. Simulations show that independent measurements can be obtained by moving the source azimuthally about the buried array yielding useful statistical ensembles. With this approach coherent processing is found to be superior to incoherent processing and can be used to identify slow coherent waves in the presence of fast incoherent waves for cases where the coherent energy is well below that of the incoherent energy. For above-critical geometries, roughness scattering was found to noticeably reduce spatial coherence, and thus this effect should be accessible to experimental examination.

Simulations have also been done to assess the importance of scattering from volume inhomogeneities. In sandy sediments such as found near Panama City, historical data suggest that volume inhomogeneities are mild (the standard deviation of density variation is about 1-2%). Using these data as input to simulations, we find that for subcritical grazing angles sediment volume scattering has a much smaller effect on coupling sound into the sediment than natural sediment roughness. Only when the roughness is smoothed would the volume contributions become significant. Simulations also show that in order to correctly model sediment volume scattering in general, it is essential that sound speed-density cross spectra be measured.

Environmental measurement systems

Sediment Conductivity Probe: Conductivity probes measure in situ sediment conductivity from which density can be derived. An important issue is the proper conversion of measured conductivity data to a spectrum of sediment density variability, a key input to scattering models. In the past year, extensive laboratory experiments were carried out to study conductivity of sediments made up of glass beads and real sands submerged in seawater. Using Archie's rule, an empirical formula to convert conductivity to density, we obtained density spectra for many laboratory samples. The results were carefully calibrated using the traditional weigh-dry-weigh method. Glass bead measurements were made with large beads, small beads and mixtures of sizes. The measured porosity was as expected for glass beads. For same size beads, Archie's parameter was found to be consistent to within 1%, and the results for different size beads and mixtures were internally consistent. This work supports the use of ArchieÕs rule for obtaining density spectra from conductivity measurements.

Measurement of sand grain bulk modulus: The grain bulk modulus is an important input parameter in Biot models of sediment acoustics. Normally, the grain bulk modulus is assumed to be the same as the quartz crystal value. However, Chotiros [1] has reported a substantially smaller value based on laboratory measurements using the unjacketed compressibility test method. For our measurements the porosity is maintained at a relatively high value (> 80%) so the sand grains are simply suspended in the liquid with very little grain-grain contact. In this case, the sound speed of the mixture is related to the bulk moduli of the liquid and the grains via Wood's equation to a very good approximation at frequencies of interest. Corrections to Wood's equation can be shown to be small via multiple scattering theory. The bulk modulus of the liquid is easily obtained by measuring the sound speed and density of the liquid alone. Preliminary results to date yield a grain bulk modulus consistent with the quartz crystal value, and the Chotiros value is excluded with high confidence.

IMPACT/APPLICATIONS

Work under this program should lead to improved high-frequency models for acoustic penetration into sediments, for scattering from sediments, and for spatial and temporal coherence within sediments. These improvements should have an impact on modeling detection and classification of buried objects. A corollary to acoustic model refinement should be a better understanding of the essential parameters that are needed for practical models. In the near term, SAX99 will provide a well characterized environment that can be used to test modeling accuracy for applied measurements.

RELATED PROJECTS

Kevin Williams is investigating biological effects on acoustic scattering from proud and buried mines using data from the 1995 ORCAS experiment. The SAX99 measurement program will benefit from the experience gained on that project.

Joe Lopes (CSS) plans to make acoustic scattering measurements from proud and buried objects during SAX99. The extensive environmental characterization to be made as part of SAX99 will be available for acoustic modeling studies of his measurements.

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